# Modeling of Particle Debris from the Target of Laser Produced Plasma EUV Sources

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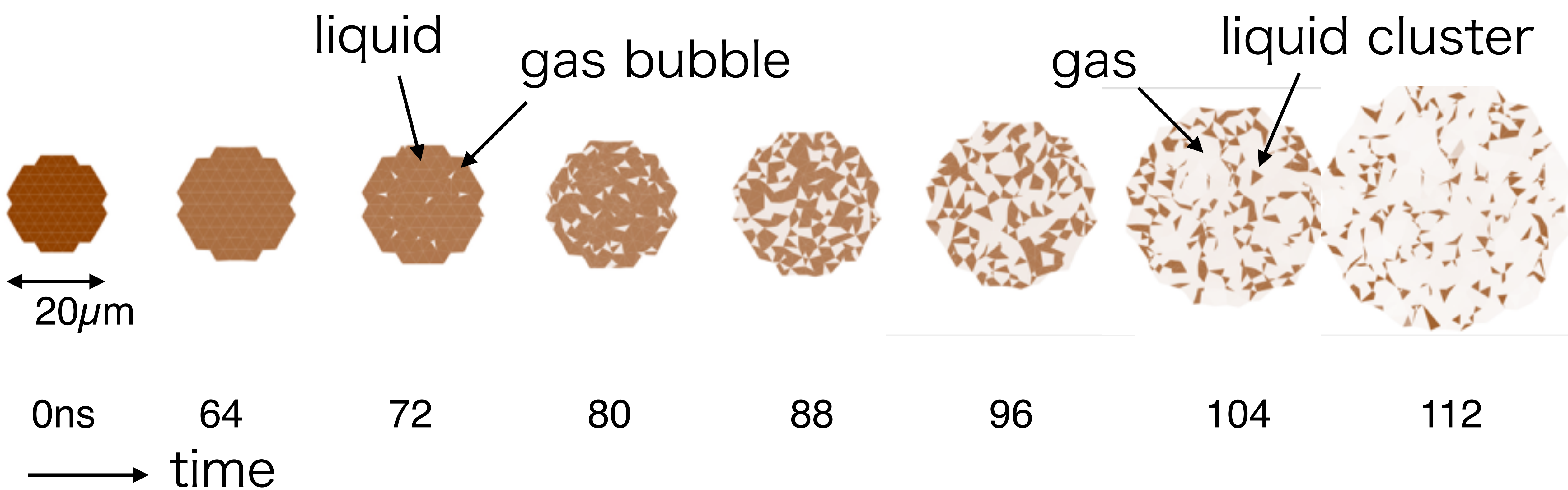
# Emission of particle debris for LPP EUV source

- Particle debris are emitted from laser ablation of Sn droplet.
- Contamination of collector optics limits the availability of the source.
- No simulation is available for the emission of particle debris.

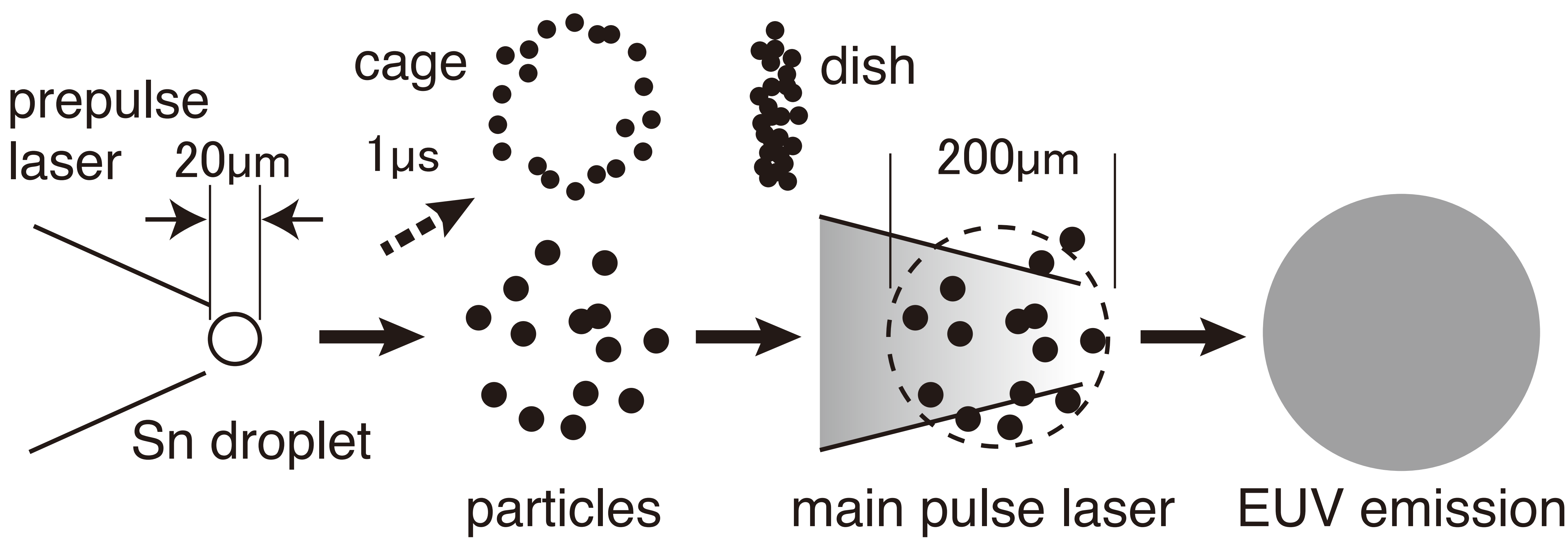
Density profile of uniformly heated droplet



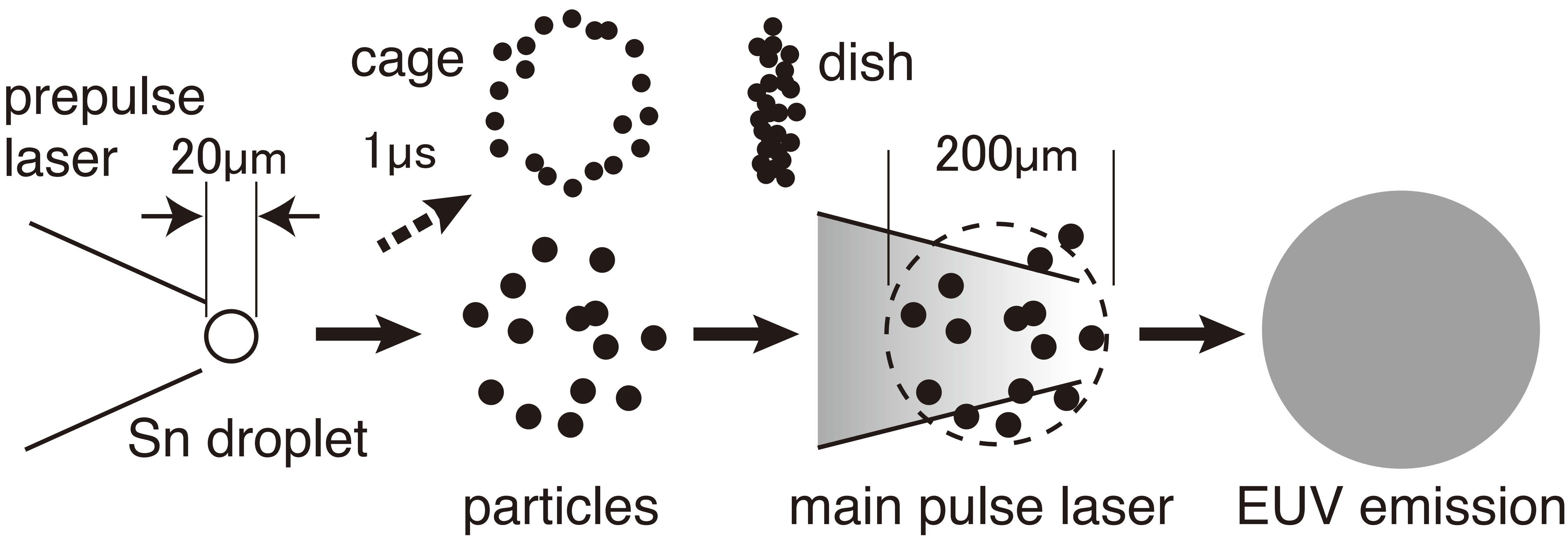

A. Sasaki, AIP Advances 7 (2017) 095005.

# High CE (>5%) using pre-pulse technique

- Droplet is broken up into particles by pre-pulse irradiation.
- Main $CO_2$ laser pulse irradiates when the cloud of particles expanded to ≈200μm, then plasmas of appropriate density and temperature for emission is produced.
- Laser is absorbed efficiently only with the particles.



# High CE (>5%) using pre-pulse technique

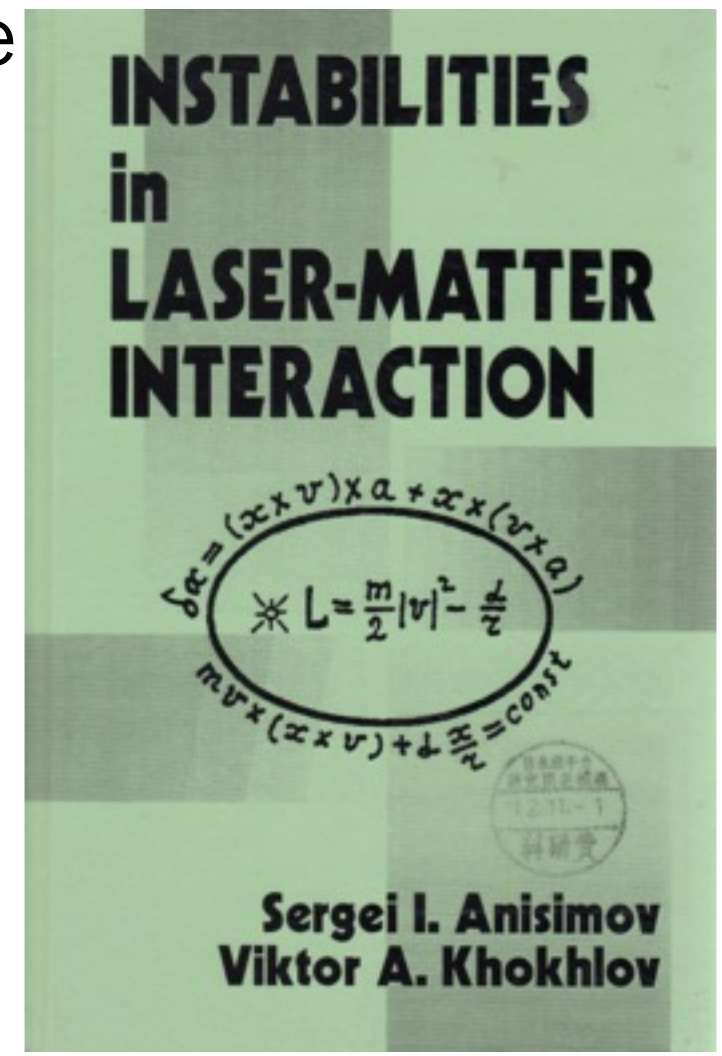



- Extensive experimental investigations have been carried out.
- Property of particles critically depends on laser irradiation.
- Observation of particles is difficult; simulation may be useful for optimization.
- Properties of particles including absorption of laser are interesting and modeling is a challenge, in the point of view of basic science.

# Present status of modeling particle debris

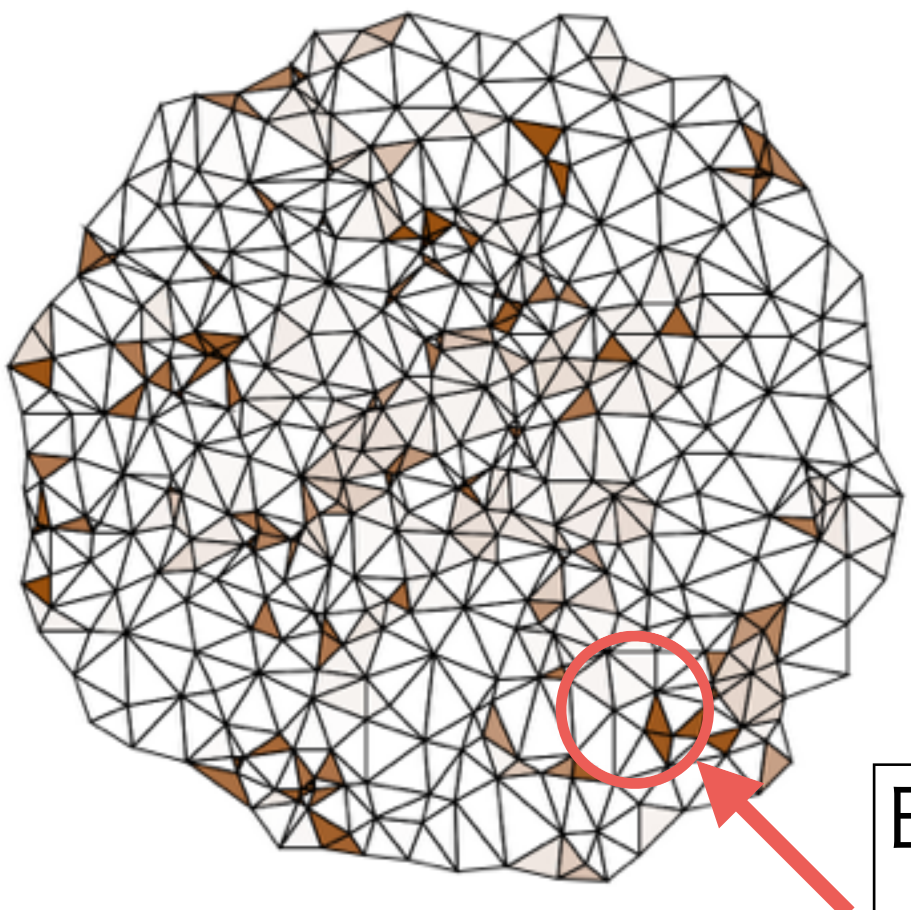
We propose Lagrangian hydrodynamics model with rezoning algorithms with which dynamics of gas bubbles in liquid and particles in gas are taken into account.

- Anisimov suggested emission of particle debris though instabilities in laser-matter interaction, did not provide methods for analysis.
- Temporal and spatial scale of MD simulation is too small.
- Present Eulerian hydrodynamics model has difficulties to take liquid-to-gas transition into account.



# Concept of Lagrangian hydrodynamics model

- Lagrangian model uses mesh moves with fluid.
- We develop rezoning algorithms to place meshes along distribution of material.



Distribution of particles is scale-free, that allows analysis at an arbitrary scale. Statistics of particles rather than development of each particle is interested.

*surface tension is small if r > 100 nm

Even expansion is a transient phenomena, thermal equilibrium stands inside the small volume. Fraction of liquid/gas can be determined using EOS.

# Basic equations

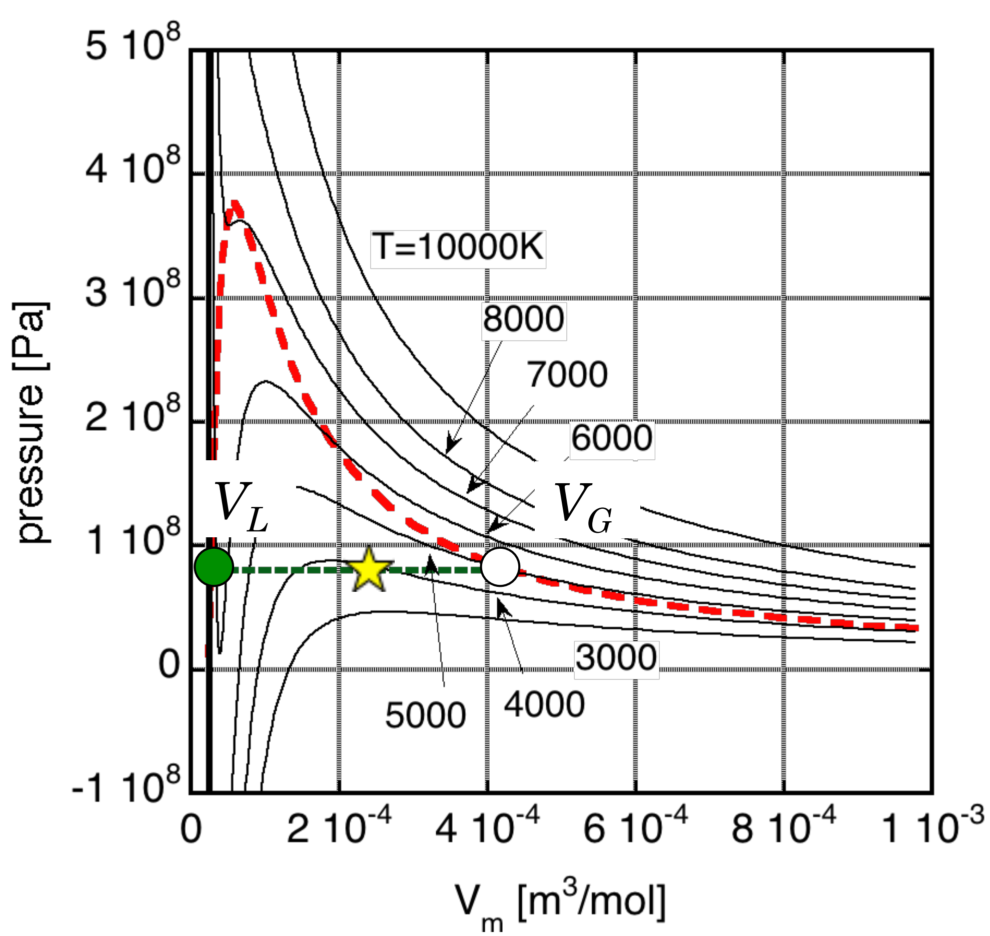
Equation of motion $\rho \frac{d\mathbf{u}}{dt} = -\nabla P$

Equation of energy $dU_m = dQ_m - PdV_m$

Van-der-Waals equation of state

$$P = \frac{RT}{V_m - b} - \frac{a}{V_m^2}$$

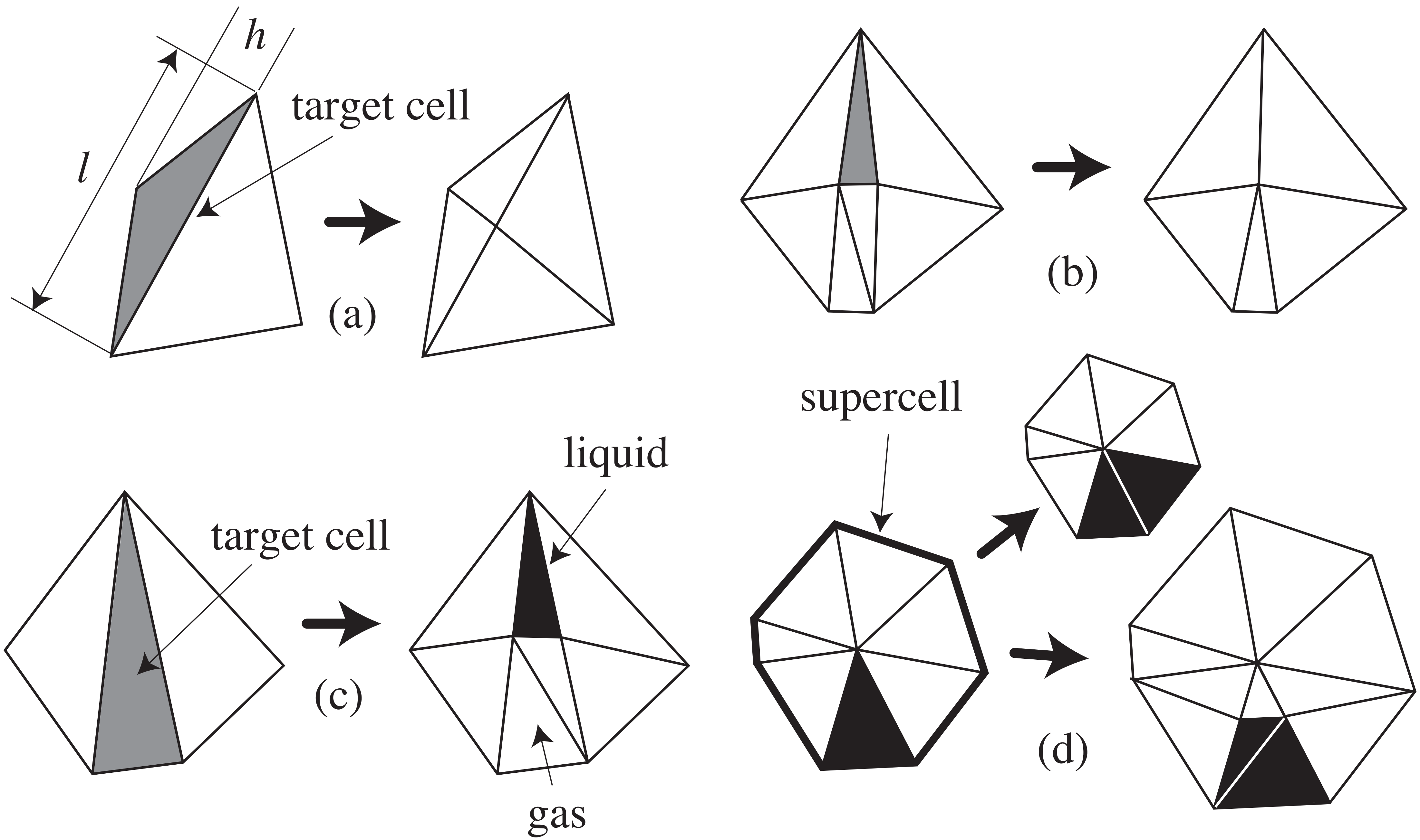
$$U_m = A_m + TS_m = \frac{3}{2}RT - \frac{a}{V_m}$$



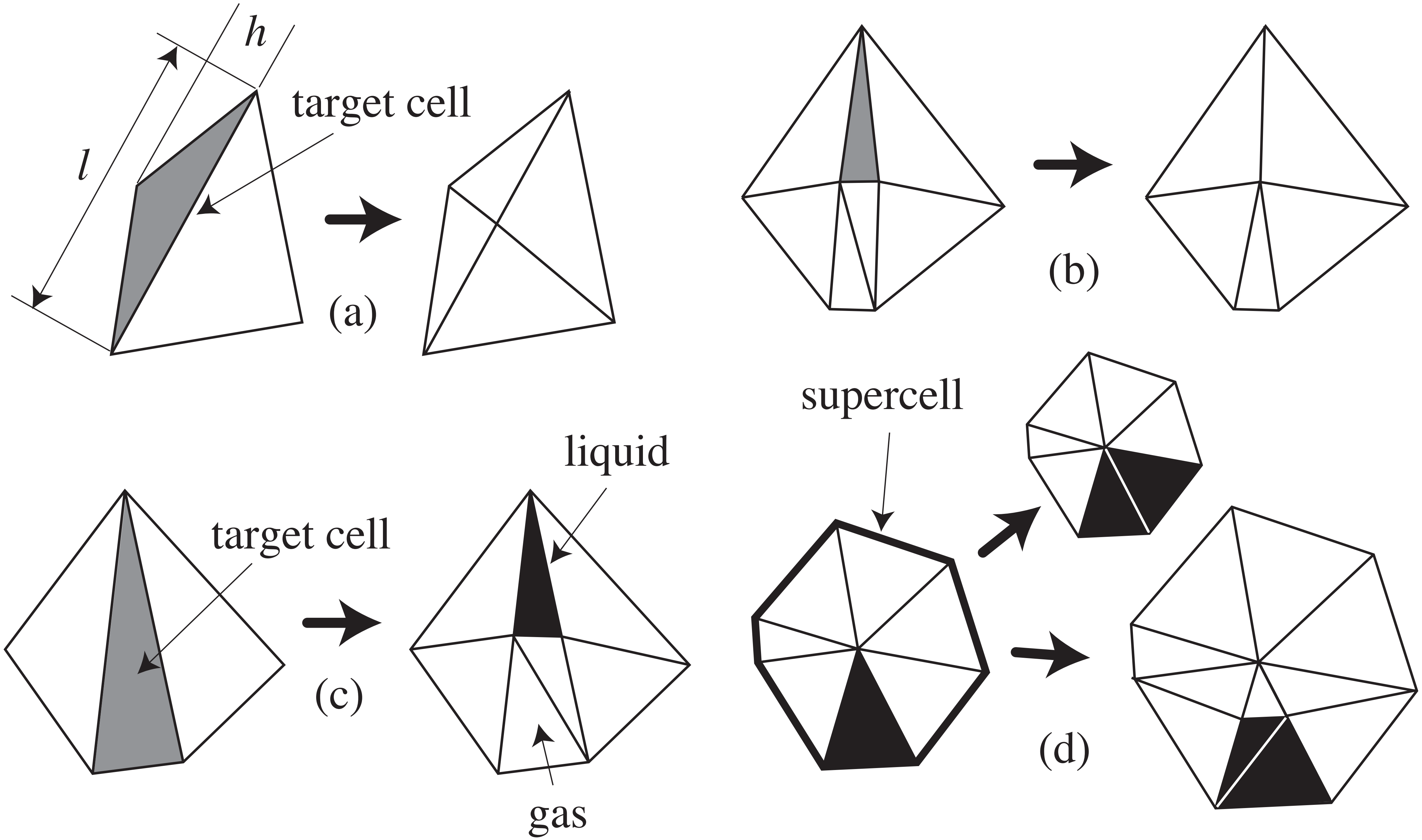

- Pressure and internal energy are given in analytical forms.
- Represents two phase condition, with ratio between liquid and gas for given temperature and density.

# Rezoning algorithms

Cell is divided or united with neighboring cells to reduce distortion of the mesh, conserving mass and internal energy.



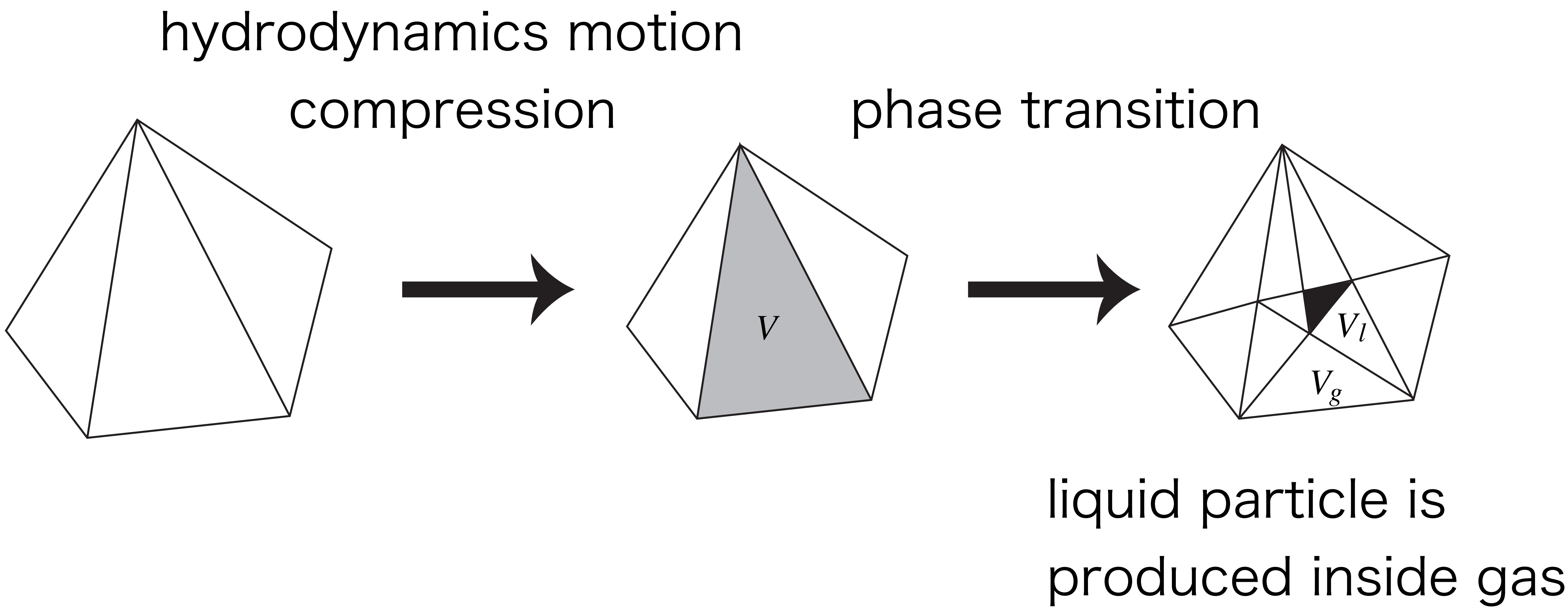
# Liquid-to-gas transition algorithms




- Cell is divided to liquid and gas regions.
- Number of liquid(gas) cells in a supercell is increased to represent continuous evaporation and condensation.

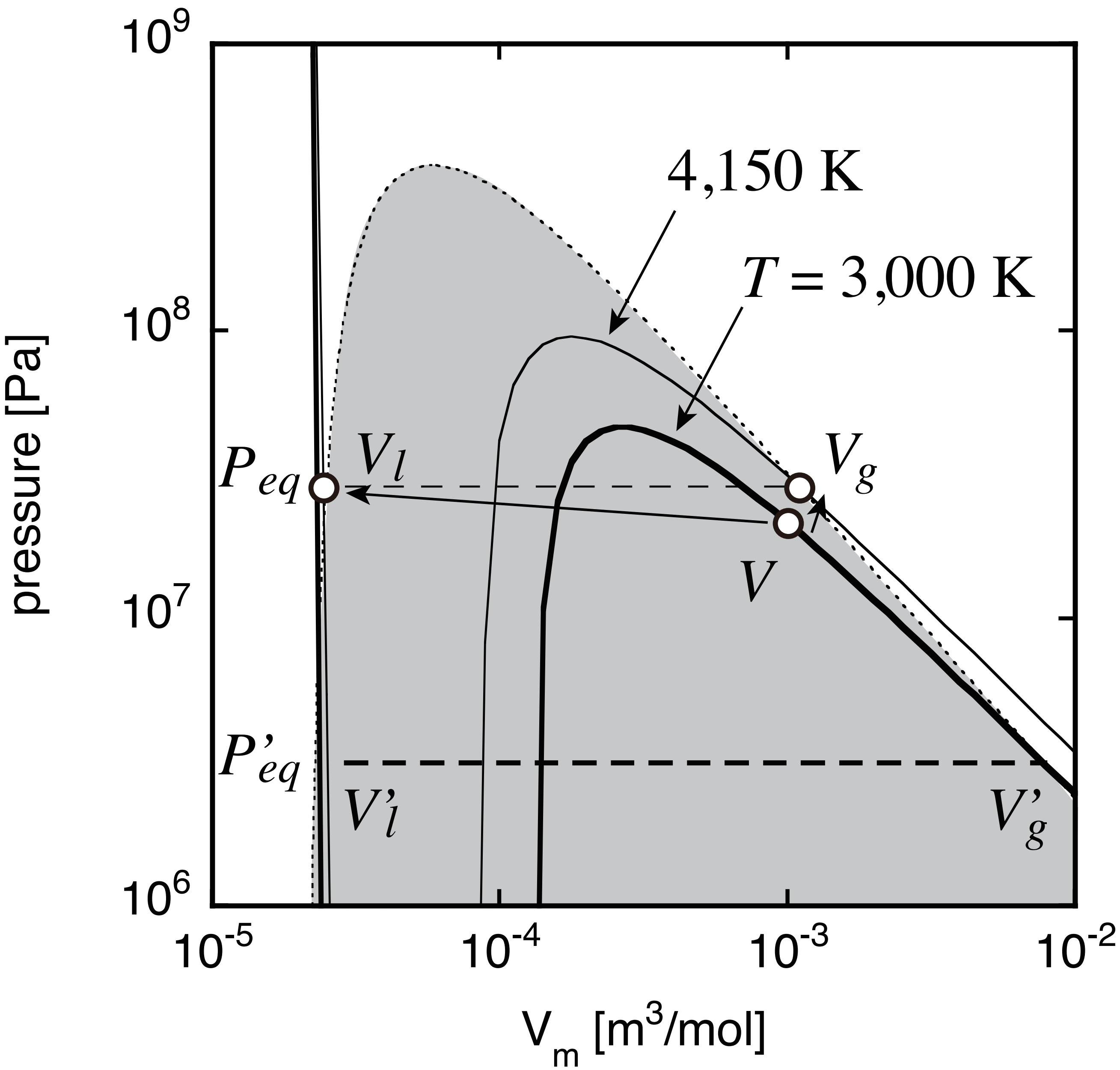
# Time splitting

- Calculation of hydrodynamic and rezoning/phase-transition are carried out alternately.
- At each time step, appropriate ratio between liquid and gas of the target cell is evaluated using EOS, and the cell is divided to have liquid and gas regions.



# Determination of ratio between liquid and gas

- Ratio between liquid and gas inside the cell is determined using EOS given the temperature and density of the cell.




- Difference of temperature before (3,000K) and after (4,150K) arises from difference of internal energy of liquid and gas phase, which corresponds to latent heat.

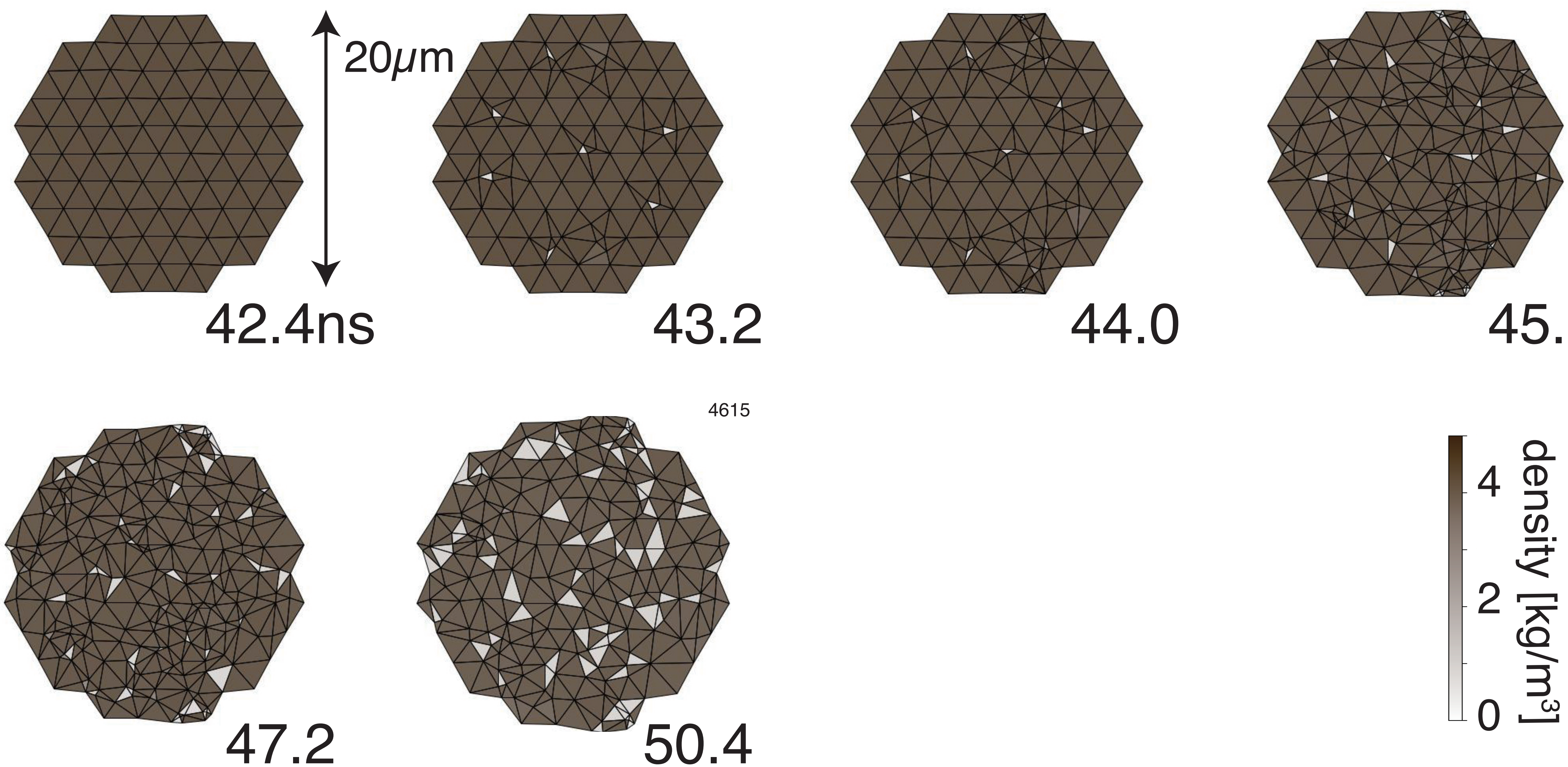
# Test cases

- Calculation of low density (gas) target agrees with 1D model.
- Temporal evolution of density and temperature is calculated for tin cylinder heated uniformly and constantly; entire material is evaporated to form gas after long time.

  initial diameter = 20 μm
  density = $5.5 \times 10^3$ kg/m$^3$
  temperature = 2,000 K
  heating rate = $2.5 - 6 \times 10^{12}$ W/mol

# Initial bubble formation

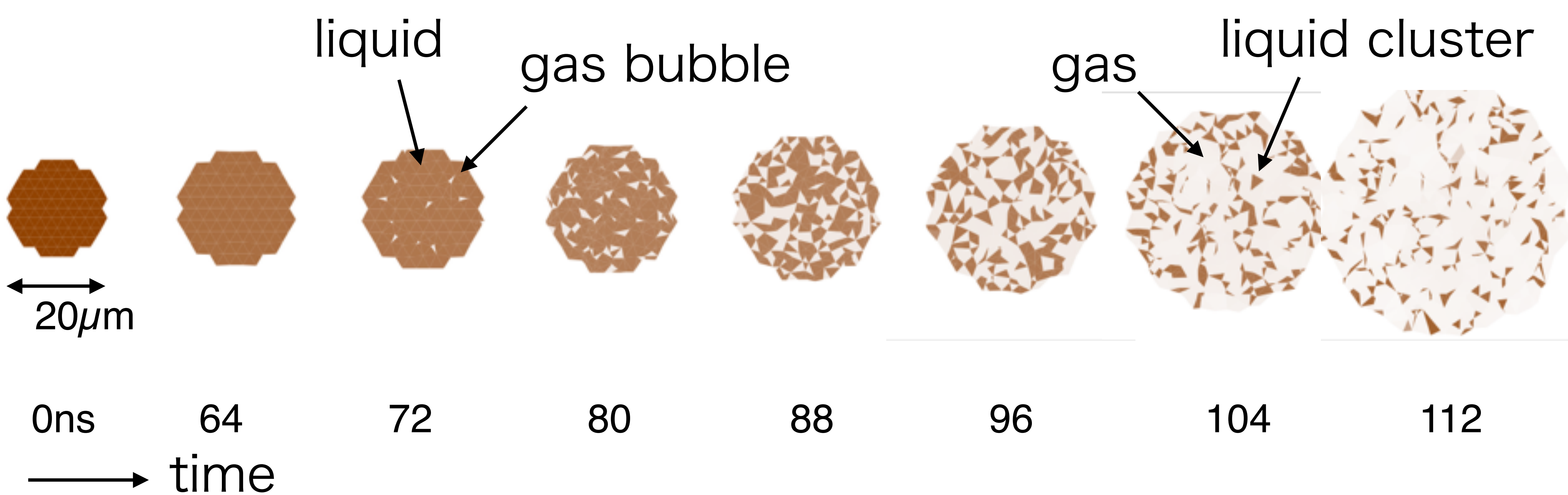
Rezoning algorithm is activated by small increase of volume to form bubbles inside the liquid target.



# Result

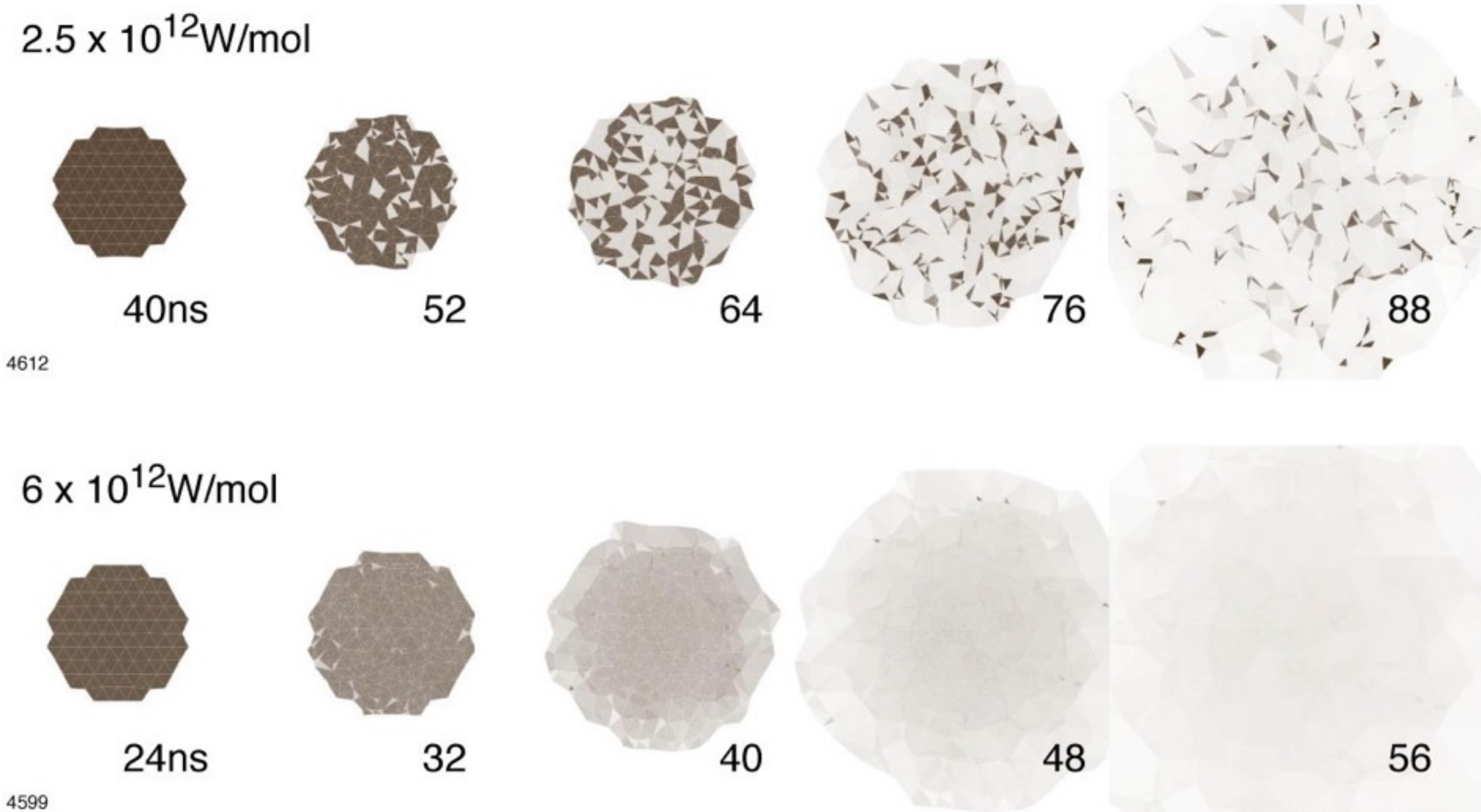
- Bubbles appear inside the liquid target, which grow to break the target into particles.
- Target is at rest until gas phase becomes dominant, then expands rapidly.

Density profile of uniformly heated droplet

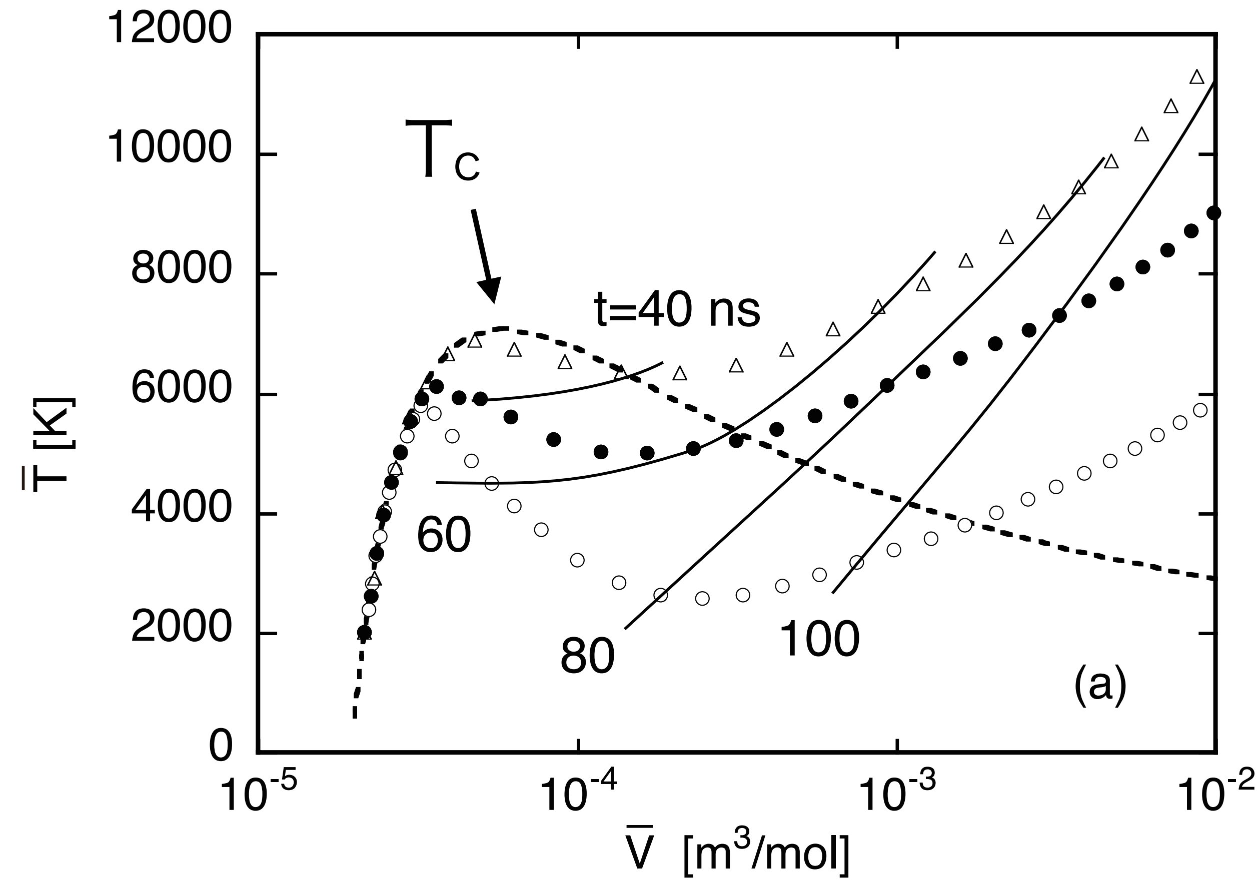


# Results for different heating rates

## Particle debris are emitted at low heating rates



# Criteria of emission of particle debris

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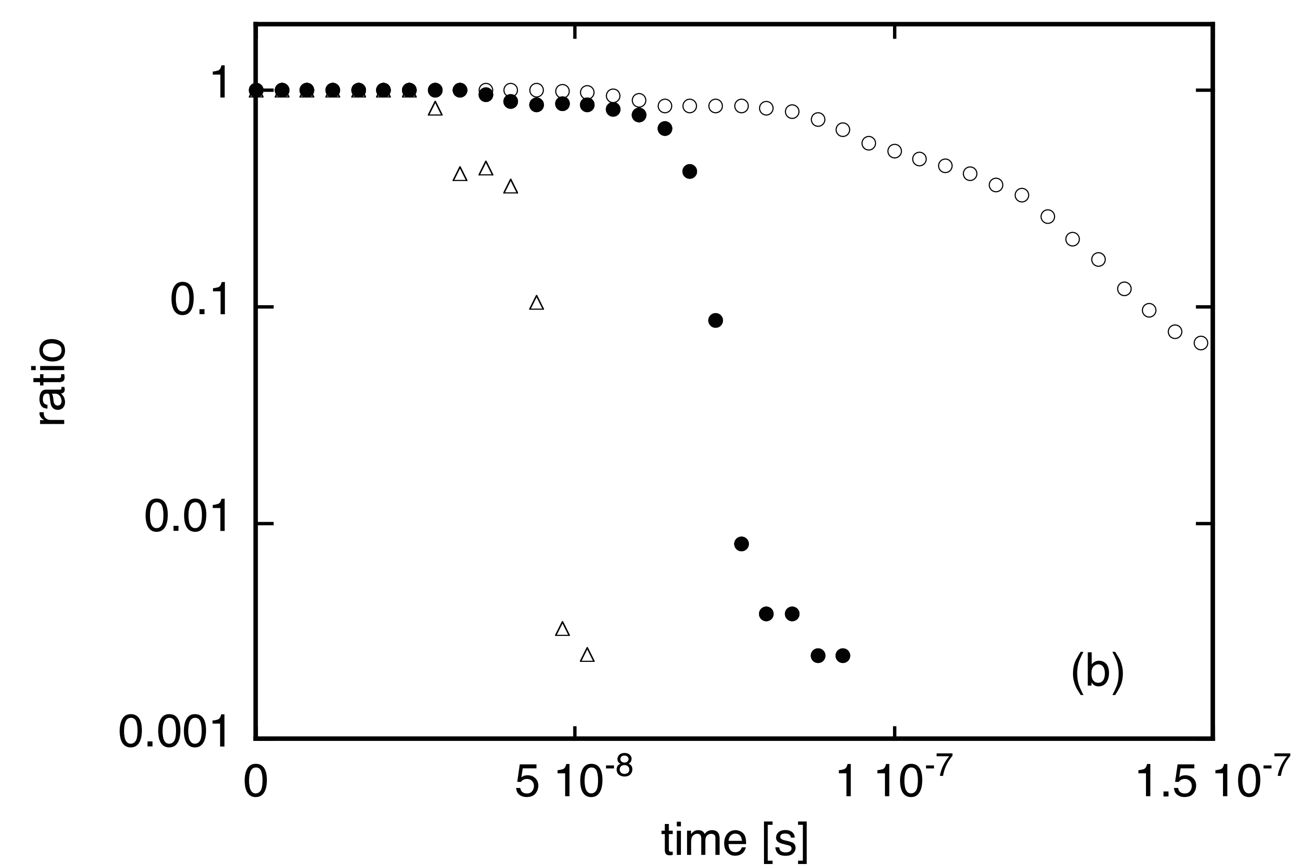
Averaged temperature and volume of entire target

2.5 Heating rate x$10^{12}$ [W/mol]

Two phase region

At small heating rates, target expands through two phase region, whereas at large heating rates, temperature immediately exceeds $T_C$ thus particle formation does not take place.




Ratio of liquid phase

# Discussion

- We investigate emission of particle debris from laser ablation of Sn droplet using hydrodynamics model with coarse grained mesh to investigate the statistical behavior of particles
- Calculations of heated Sn target show that particles are emitted at relatively low heating rates.
- Emission of particle debris from shock driven target will be investigated; algorithms to track motion of particles for a long time may be necessary.